Failure and damage analysis of the cast element

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***ABSTRACT*: *In the paper the potencial risk of failure and damage evolution in the cast bar operated in the temperature range from +20^{o}C(293K) to -60^{o}C(213K), under dynamic loading, has been analysed by several approaches. The strength properties and fracture toughness of cast steel have been determined in the above range of temperatures. The computer simulation of the stress and displacement states as well as damage evolution in the cast bar have been performed at temperatures of +20^{o}C(293K) and -60^{o}C(213K), assuming two hypotheses of material deformation: Huber-Mises yield criterion and Gurson-Tvergaard-Needleman plastic potential model. To estimate the influence of temperature on the cast steel fracture mechanism, the fractographic examinations of tested specimens were made. The assessment of the reliability of cast element under dynamic loading at various temperatures has been performed using R-6 Code Software. As a result the admissible defect size and the fracture mechanisms at different temperatures have been estimated.*

INTRODUCTION

The analysis of several hundred accidents, which took place in the previous century, showed the following main reasons of structural elements failures: fatigue, residual stresses, high temperature of plastic-brittle transition, defects, too low value of fracture toughness and insufficient knowledge of fracture mechanisms. The problems associated with the last four reasons will be discussed in this paper on the basis of failure analysis of running gear element.

Some years ago a number of failures of rolling stock components operated at low temperatures were noticed. Cracking took place mainly at low temperatures when railway cars were overloaded dynamically.

The main reason of sudden failures was damage evolution, which triggered macroscopic fractures. Thus, it was important to analyse the stress and displacement states, damage evolution as well as to estimate the admissible defect size in a tested element at different temperatures.

MATERIAL, EXPERIMENTAL PROCEDURE AND RESULTS

The aim of the work was estimation of the risk of bar failure in the temperature range from +20°C(293K) to -60°C(213K). This work was made using experimental methods of fracture mechanics, fractographic examinations, software for assessing the integrity of elements containing defects and numerical modelling of stress, displacement and damage evolution basing on damage mechanics. To realize these aims some experimental tests were performed.

The tested element was bar made from the low carbon cast steel. After casting the bar was normalized and annealed.

Figure 1: Scheme of the cast bar.

The strength properties and fracture toughness of cast steel under dynamic loading were determined in the range of temperature from +20°C(293K) to –60°C(213K). The data obtained in these tests are given in Table 1. Because of the dynamic character of loading the fracture toughness was determined by Instrumented Charpy Pendulum, using precracked samples.

The dynamic fracture toughness has been measured using 3-point bending samples. The thickness of samples was equal to 10 mm. The critical value of dynamic J integral J_{Id} was determined in the temperature range from +20°C (293K) to –60°C (213K) using multi specimen technique.

The values of stress intensity factor K_{IQ} calculated from J_{Ic} are given in Table 1, too. The details concerning the applied equipment and method used are presented in [1,2].

TABLE 1: The results of strength and fracture toughness testing under dynamic loading

Temperature (°C) / (K)	Yield stress $R_{0.2}$ (MPa)	Ultimate tensile strength R_m (MPa)	Stress intensity factor K_Q (MPa*m$^{1/2}$)	Critical value of J-integral J_{Id} (MJ/m^2)
+20 / 293	282.1	504.2	163.7	0.122
-30 / 243	335.9	552.8	98.3	0.044
-45 / 228	362.3	571.2	86.4	0.034
-60 / 213	386.3	588.9	59.3	0.016

Failure Assessment Diagram

One of the methods adopted for an assessment of the potential risk of failure in structural elements is method based on the Failure Assessment Diagram (FAD), shown in Figure 2. In the failure diagram the condition of brittle fracture is described on ordinate by the quantity denoted by $K_R = K_I / K_{Ic}$ or by $K_r = K_I / K_{Ic}$, while the condition of ductile fracture, expressed by an applied-to-general yielding load ratio is determined on abscissa by the quantity denoted by $S_R = P / P_l$ or by $L_r = P / P_l$.

The loads corresponding to the points lying under the FAD diagram are corresponding to the safe loads, those lying outside indicate emergency conditions. The safety factor is determined by the ratio of sections OB/OA. The method of calculations based on FAD has been developed further by British Energy in the form of a computer programme called R-6 Code [3].

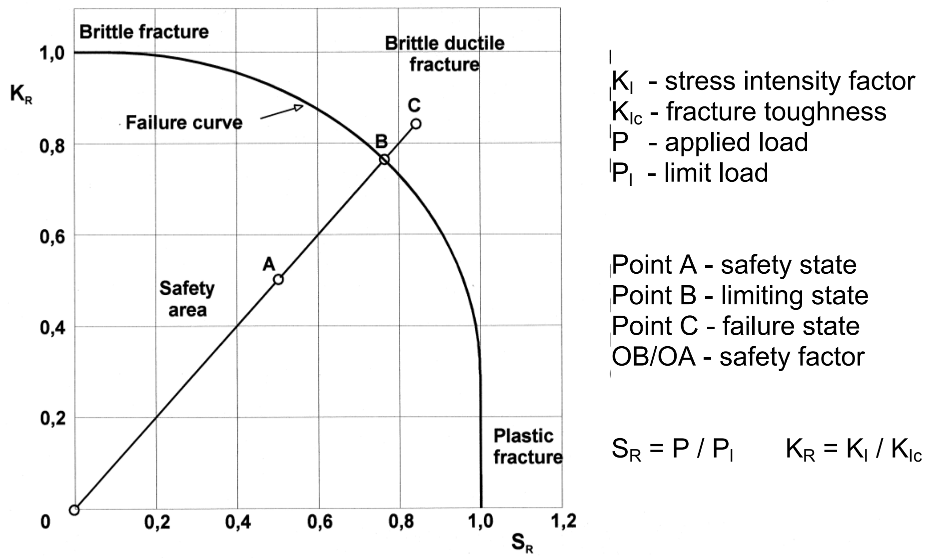

Figure 2: Failure Assessment Diagram.

Assessing the Integrity of the Bar containing Defects

For elements containing defects, which are used in service it is necessary to predict their behaviour under changeable service conditions. The railway cars are exploited at different temperatures and the fracture toughness of bars is reduced with decreasing temperature. Therefore the safety change was estimated for various temperatures. For this purposes the Failure Assessment Diagram (Figure 2) was used. As an example, the behaviour of cracked bar with decreasing temperature was analysed. The crack length was equal to 2 mm and the thickness of casting was equal to about 10 mm.

The safety analysis was made for residual stress equal to $R_{0.2}$, allowing for changes in temperature. When the temperature changed from +20°C(293K) to –60°C(213K), the safety of bars changed too, as it is shown in Figure 3.In this diagram the admissible defect sizes at different operating temperatures are shown.

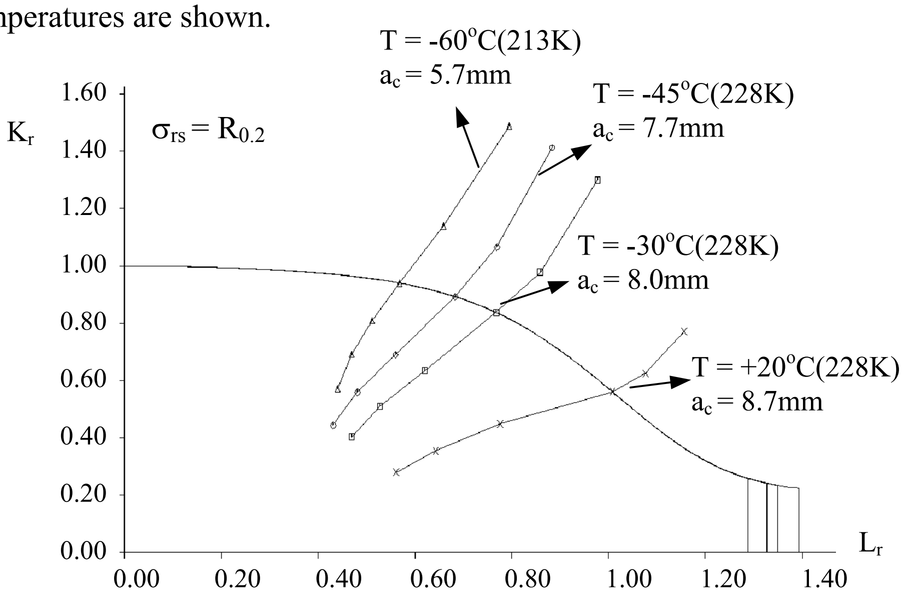

Figure 3: FAD for the cast bar, for residual stress equal to yield stress.

Fractographic Examination

To estimate the influence of temperature on the cast steel fracture mechanisms, the fracture surfaces of the tested specimens were examined by means of scanning microscope. The results of observations show that at a temperature of +20°C (293K) (Figure 4) the ductile fracture took place. In the temperature range from –30°C (243K) (Figure 5) to -45°C (228K) (Figure 6) the mixed mode of fracture has occurred. At –60°C (213K) (Figure 7) the transgranular cleavage fracture was observed.

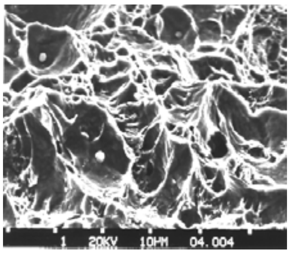

Figure 4: Temp.+20^{o}C(293K)
Ductile fracture

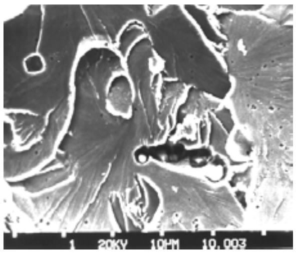

Figure 5: Temp. -30^{o}C(243K)
Mixed mode of fracture

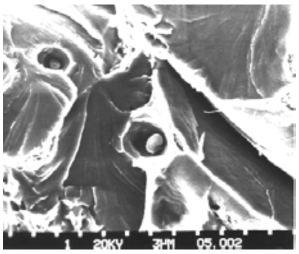

Figure 6: Temp.-45^{o}C(228K)
Mixed mode of fracture

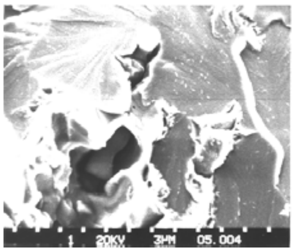

Figure 7:. Temp. -60^{o}C(213K)
Cleavage fracture

Numerical Modelling of Stress State, Displacement State and Damage Evolution in the Cast Bar

The numerical calculations of stress state and displacement field for the cast bar have been performed according to two hypotheses of deformation: the Huber-Mises (HM) hypothesis for isotropic material and the Gurson-Tvergaard-Needleman (GTN) plastic potential model [4, 5] for porous material. The two temperatures of operation were assumed: +20^{o}C (293K) and -60^{o}C (213K). The following loadings, acting on the cast element, were used: 480kN, 1920kN, 3360kN, 3840kN, 4320kN, 4800kN, 5280kN and 5760kN [6]. In the GTN model, the initial porosity f_o and the porosity resulting from voids nucleation f_N were taken into account. The initial porosity f_o has been set to 0.5% and the porosity resulting from voids nucleation f_N has been equal to 0.5%. The calculations were made in one quarter of the cast bar assuming symmetry of the element. The examples of the stress and displacement state in ahe quarter of the bar are presented in Figures 8 and 9 respectively, while the damage evolution is shown in Figure 10.

The results concerning two temperatures of bar operation +20^{o}C (293K) and -60^{o}C (213K), eight cases of stress states, displacement fields and voids volume fraction for growing loadings, calculated on the basis of two hypotheses HM and GTN will be presented during conference in the form of colour animation.

GTN model, loading 5760 kN	
Temp. +20^{o}C(293 K)	Temp. -60^{o}C(213 K)

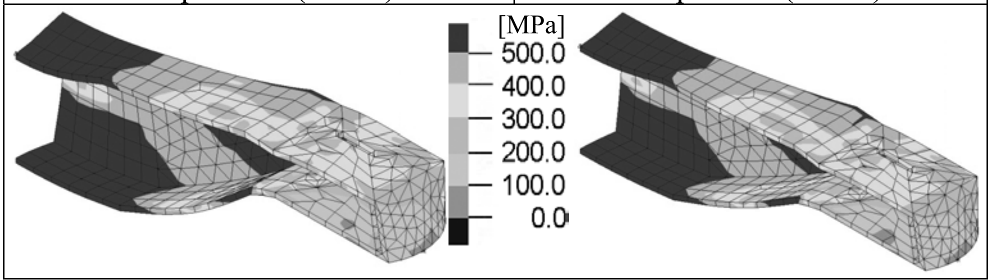

Figure 8: Stress state in the cast element.

GTN model, loading 5760 kN	
Temp. +20^{o}C(293 K)	Temp. -60^{o}C(213 K)

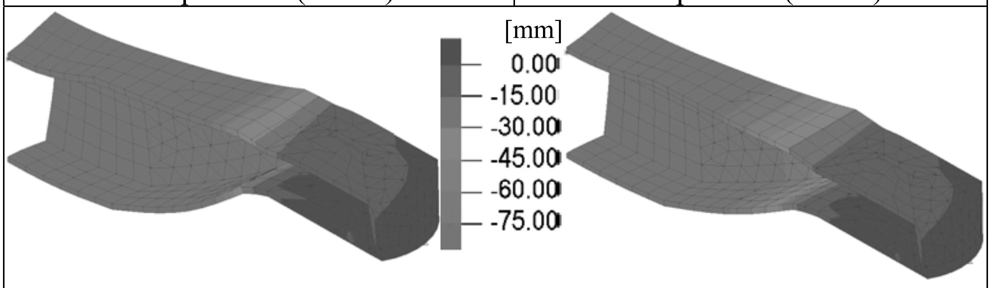

Figure 9: Displacement field in the cast element.

GTN model, loading 5760 kN	
Temp. +20^{o}C(293 K)	Temp. -60^{o}C(213 K)

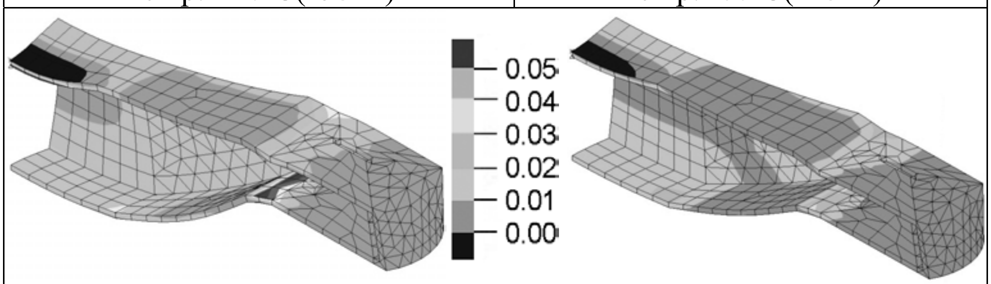

Figure 10: Void volume fraction in the cast bar.
Levels of void volume fraction: 1%, 2%, 3%, 4%, 5%.

Results of Numerical Calculations

Figure 8 presents the results of calculation of stress fields in the quarter of the bar. The stress fields have been obtained according to the GTN hypothesis at working temperature +20^{o}C (293K) and -60^{o}C (213K) under maximum applied loading, which was equal to 5760kN. In both temperatures the stress values are greater than the yield stress which is equal to 282MPa at temperature +20^{o}C (293K) and 386MPa at temperature -60^{o}C (213K). It demonstrates the ability of plastic strain in the cast element.

In Figure 10 the areas of higher voids concentration are shown. In this area the failure process is expected.

Summary

Along increasing loading the following changes are observed in selected regions of the cast element:

a) under loading over 3360kN the efective stress exceeds the yield stress and plastic strain take in certain region of the cast element,
b) starting from loading 4320kN and at temperature +20^{o}C (293K) the void volume fraction increases considerably reaching value of 5% at 5760kN and covering more than 1% of the element surface.

With decreasing working temperature of the cast element from +20^{o}C (293K) to -60^{o}C (213K) the following changes take place in the cast bar:

a) the strength of the cast increases by 37%,
b) the fracture toughness decreases by 87%,
c) the admissible defect size calculated with the computer program R6 Code decreases from 8.7 mm to 5.7 mm,
d) fracture mechanism changes from ductile to brittle,
e) at temperature -60^{o}C (213K) the analysis of the FAD diagram and fracture mechanism indicate trace of plastic deformation which may prevent the brittle fracture.

Concluding Remarks

- Failure risk of the cast element increases essentially below temperature -30^{o}C (243K).
- The numerical analysis of the deformation process using the GTN model provides more information concerning the failure process than the HM model.
- Stress and displacement fields have the same character for both models for lower loading up to the 3840kN. The essential differences in using one of discussed models can be observed when loading increases above 4320kN.

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